Design and Performance Analysis of a Low Cost Light Energy Harvester for Wireless Sensors

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Abstract--**Developments over the past decade in wireless and sensor technology have resulted in the growth of new applications for Wireless Sensor Networks (WSNs). One of the most popular areas for WSNs is the Built Environment Network (BEN), which comprises a wide variety of applications such as energy monitoring/smart homes, surveillance and healthcare applications. Such WSNs normally consist of a large number of devices with sensing, communications, and limited processing capabilities. These devices are very power constrained, as they typically depend on a small battery. Developments in recent years have led to an improvement in the energy efficiency of both hardware and software, which has resulted in increased lifetime of wireless sensors, but with limited battery capacity and size, real world lifetime is typically limited to 5 - 10 years.**

This paper presents a simple low cost, light energy harvester, that can easily be implemented with existing wireless sensor technology, to dramatically increase lifetime and remove the need for batteries. A WSN with nodes powered only by the presented harvester is deployed in an office, and results show that it can fully function in an environment where light is available for only 23.8% of the time.

Index Terms—**Wireless Sensor Networks (WSN), energy harvesting, supercapacitor**

I. MOTIVATION

The greatest challenge faced by wireless sensors is their very limited energy supply. Developments in the field of electronics has meant that wireless sensors have become smaller, cheaper and electrically more efficient. However, developments in commercially available battery technology have been slower and remain the main constraint on the lifetime of WSNs. In certain wireless sensor applications such as in hostile environments, the replacement of batteries may not be possible and even if possible the associated cost of battery replacement may outweigh the cost of the device. The work in this paper focuses on incorporating a simple energy harvesting technology to wireless sensors with the aim being to provide longer lifetime.

Several different sources of energy are available for harvest from the ambient environment, with solar/light irradiance, thermal/temperature gradient and mechanical/vibration being the most popular and cost effective. Each of these energy sources offer their own advantages/disadvantages and energy potential.[1] From these three possible energy sources, light energy harvesting technology is the most mature and widely available in almost all environments. Until recently the majority of wireless sensor applications harvesting light energy have focused on harvesting natural light in outdoor locations with much of the research focusing on the design of maximum power point tracker (MPPT) circuits to improve the efficiency of the solar harvesters.[2] [3] [4]

While the energy available from natural light sources is greater than that of artificial light, many typical wireless sensor deployments will be indoor environments where the availability of natural light is limited and often the only source of light is artificial.

The levels of energy available from artificial light are much less than that of natural light and in many cases the incorporation of a MPPT circuit is not feasible, as this circuit itself may consume more energy than is being harvested from the artificial light source. For this reason a simple low cost, low component approach is often more suited for indoor deployments and the work presented in this paper provides performance analysis and design guidelines for a real deployment.

II. METHODOLOGY & RESULTS

When developing any energy harvesting system the designer must first decide which approach to take and what components to use. The approach taken directly relates to the deployment location and the energy demands of the wireless sensor. Section A of this paper includes a review of the various light energy harvesting components and highlights their advantages/disadvantages, along with the key selection parameters of each. Following this review, the design of a simple low cost light energy harvester has been proposed in Section B. Sections C, D and E include the necessary tests required to find the optimal deployment locations and to verify that the harvester can meet the demands of the WSN. The final section of the paper includes long term deployment tests of the proposed harvester in a real world environment.

A. Review of Light Energy Harvester Components

As with any energy harvesting device, the light energy harvester consists of five main components: the energy source, energy harvester, energy storage element, energy management circuit and the wireless sensor.

Photovoltaic Cells

The energy source available to any light/solar energy harvester is light and to harvest this energy, Photovoltaic cells, more commonly known as Solar cells, must be used. Photovoltaic cells essentially convert light energy into electrical energy and have a similar behavior to a voltage controlled current source, thus providing a relatively steady voltage output and a variable current proportional to the light illuminance. It must be noted that the current of the photovoltaic cell is affected by both the density and spectrum of the light. There are three main types of photovoltaic cells commercially available: polycrystalline, monocrystalline and amphorous, each presenting their own advantages and disadvantages.

- *Polycrystalline* cells are commonly found in outdoor applications and have a sensitivity range from 500nm to 1100nm. This type of cell suffers from impurities which degrade the cell efficiency by up to 20% over the first 100 operating hours. Apart from this the main advantages are that they fall into the medium price range and typically offer power conversion efficiency of 13%.[5]

- *Monocrystalline* cells can be used both in indoor and outdoor applications as they have a sensitivity range from 300nm to 1100nm. This type of cell typically offers power conversion efficiency ranging from 15 to 19% and as the material does not contain any impurities, the efficiency does not degrade over operating time.[5]

- *Amphorous* cells are more suited to indoor applications as they have a sensitivity range of 300nm to 600nm, are not sensitive to the upper light spectrum and thus cannot take advantage of natural light. This type of cell offers efficiency of approximately 5% and like polycrystalline cells they suffer degradation over operating time.[5]

The proposed deployment location is the main determining factor on the type of photovoltaic cell used. The deployment location used in this paper was a typical office. Within this environment the primary available light source is artificial, indoor fluorescent light, but as the office has windows, natural light will also be available at some locations during certain periods. Monocrystalline photovoltaic cells are the most suited type of photovoltaic cell for this deployment as their wide sensitivity range means that they can harvest energy from both the natural and artificial light sources available.

Energy Storage

The energy storage element of the harvester is needed to store energy for periods of demand and during periods when no energy is available for harvest. This energy storage element must ensure that enough energy can be stored to allow the wireless sensor operate continuously at the chosen deployment location. The two main types of energy storage used are rechargeable batteries and electrochemical double layer capacitors (commonly know as supercapacitors).

- *Rechargeable Batteries*: The two main types of rechargeable batteries are Nickel Metal Hydride and Lithium ion, both of these rechargeable batteries have the ability to store a larger amount of energy in comparison to electrochemical double layer capacitors; thus allowing the wireless sensor to operate longer during periods when no light is available for harvesting. The main disadvantages of rechargeable batteries are that they can only be charged and discharged a limited number of times, typically around 1000. They require additional circuitry to ensure effective charging. Also, given the typical low energy levels available from indoor light, as well as the energy losses experienced in the charging process, they become almost impossible to recharge without needing a large number/size of photovoltaic cells.

- *Electrochemical Double Layer Capacitors* are commonly known as Supercapacitors; these can only store a very small amount of energy in comparison to rechargeable batteries and typically have a larger leakage current than rechargeable batteries, which severely limits their long term energy storage capability. However the main advantage of this type of energy storage is that they do not experience any memory effect, can be recharged up to 1 million times and do not need any additional circuitry. If using a supercapacitor there are several features that must be considered.
    - *Capacitance Value* – the larger the capacitance value, the more energy that can be stored.
    - *Voltage Rating* – the voltage rating is the maximum voltage that the supercapacitor can be charged to, as charging any higher than this voltage can damage the supercapacitor. It should also be remembered that the capacitance value is stated at the voltage rating, so the closer the supercapacitor is charged to its voltage rating the more energy is stored.
    - *Equivalent Series Resistance (ESR)* – it is important to ensure the ESR of the supercapacitor is very low. If ESR is too high, a large voltage drop will occur on the supercapacitor when current is drawn from it.
    - *Leakage Current* –the leakage current of the supercapacitor must be as low as possible, as the higher the leakage current, the quicker the supercapacitor will self-discharge.

As already stated the majority of light for harvesting from the deployment environment is artificial indoor light. The levels of energy available for harvesting from artificial indoor light can be less than 1/10th of that of natural outdoor light.[1] Rechargeable batteries are not particularly suited to the storage of these very low levels of energy due to the energy losses incurred by the charging process and the memory effect that trickle charging creates. Supercapacitors however can be charged more efficiently at these energy levels, do not suffer any memory effect, are generally smaller and lighter than rechargeable batteries and need only minimal additional circuitry. For these reasons, the Supercapacitor was deemed the most appropriate approach for the proposed harvester.

Energy Management Circuit

The Energy Management Circuit can have many roles and they vary greatly depending on the components and setup used. The main aim of this circuitry is to effectively manage harvested energy, thus ensuring that energy is available for the wireless sensor even during periods when no energy is available for harvest. In addition the circuitry must also ensure that the voltage supply to the wireless sensor is kept within its operating range. The energy management circuit can range from a simple diode setup that prevents energy being discharged from the energy storage element, to more complex circuitry such as MPPT and necessary charging circuitry. MPPT ensures maximum energy is extracted from the photovoltaic cells at all times, while additional charging circuitry is required when using rechargeable batteries to ensure that they remain efficient at storing energy.

B. Simple Light Energy Harvester

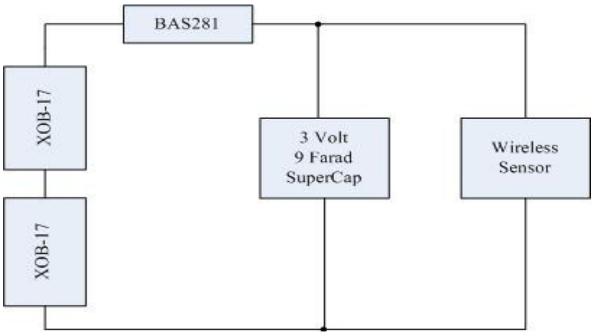

Figure 1 Proposed simple light energy harvester

Figure 1 is a schematic of the simple proposed energy harvester. Findings from the initial review provided the basis for the chosen low cost light energy harvester approach consisting of only photovoltaic cells to harvest the energy, a schottky diode to manage the energy and a supercapacitor to store the energy. The main advantages of this simple approach are: no further circuitry required; the limited recharge cycles and memory effects normally associated with rechargeable battery technologies are removed; and an overall reduction in size and weight is achieved. The one downside to this approach is that the supercapacitor does not have the ability to store the same quantity of energy as a battery.

The photovoltaic cells used are the monocrystalline XOB17-04x3 from IXYS [6], which provide a nominal voltage of 1.5V and up to 11.5mA in direct sunlight, while occupying an area of only 22mm x 7mm. The proposed setup uses two of the XOB17-04x3 in series to provide a maximum of 3V, which is within the operating range of the wireless sensor and removes the need for any step up/ step down voltage regulator circuitry. The diode used in the circuit is a BAS281 small signal schottky diode from Vishay [7], this diode has a very small forward voltage drop and very low reverse leakage current (200nA), which ensures low energy loss during the charging process and minimal energy discharge back to the photovoltaic cells during periods of low harvestable energy potential (Night). The supercapacitor used was a 3V 9 Farad, more detail will be given in Section E as to the selection of this supercapacitor.

C. Deployment Environment & Hardware Evaluation

Before deploying the WSN consisting of the proposed light energy harvester powered wireless sensors, a survey of the deployment area must be performed. The survey will help find the optimal deployment positions to ensure the harvester will generate enough energy to meet the demands of the wireless sensor. This survey provides the designer with the range of power levels available from the harvester within the deployment environment and highlights any limitations. Our deployment area was a typical office environment offering a mix of artificial and natural light. The light levels within the office were first measured using a handheld Lux meter. The measured levels ranged from only 150 Lux in corner locations to 11000 Lux directly under the fluorescent light. It should be noted that the measurements were all performed between 12.00PM – 2.00PM on a bright day in June; if the measurements had been taken on an overcast day in the middle of winter, some locations such as the window would have shown lower Lux levels.

Maximum Power Measurement

With the level of light known at various locations throughout the office, the next step was to measure the maximum power that the harvester can generate at these light levels, this was done by measuring both the current and voltage produced by the two solar cells in series while connecting a range of resistance values across them. The resistance values ranged from 0Ω to 300KΩ. Figure 2 shows the setup used to measure both the current and voltage over a range of resistive loads.

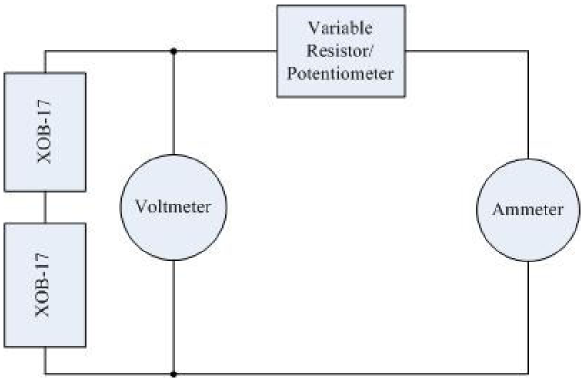

Figure 2 Setup used to measure maximum power

Each current and voltage measurement is then multiplied together to find the maximum power possible from the two solar cells in series. This experiment was repeated at different locations. Table 1 shows the Lux levels along with the maximum voltage, current and power measured at all eight different locations within the office.

TABLE 1 RESULTS FROM SURVEY OF DEPLOYMENT ENVIRONMENT

Location	**Light Level (Lux)**	**Max Volts (Volts)**	**Max Current (Amps)**	**Max Power (Watts)**
Bench	1100	2.565	57µA	88µW*
Fluorescent (facing up)	11000	3.151	524µA	1.25mW
Fluorescent (right angle)	2600	2.924	159µA	290µW
Desktop Light	3500	3.035	180µA	320µW
Corner 1	230	2.09	15µA	18µW*
Corner 2	150	2.25	21µA	30µW*
Window Location	5300	3.131	423µA	861µW*
Ceiling (facing down)	250	2.38	31µA	46µW

** These locations are affected by conditions outside*

As expected the two corners locations of the office offered the lowest light levels with values of only 150 and 230 Lux. The result of this is maximum power of only 18µW and 30µW respectively at these locations using the proposed two solar cell setup. When the effects of charging losses and the small leakage of the supercapacitor are taken into account, the potential available energy is even less. These very low energy levels would not be sufficient to run even the lowest power applications.

The highest Lux levels of 11000 and 5300 were recorded directly under the 72W Fluorescent Light (5cm) and in the window location. The resultant maximum power levels were 1.25mW and 861µW respectively. Interestingly, the Lux and power levels drop to 2600 Lux and 290µW respectively at this location directly under the fluorescent light when the solar cells are positioned perpendicular to the light. The measurements all indicate the maximum power possible at the various locations, but do not give a representation of the real power potential. To calculate the overall available power, the number of hours of available light at each location must be taken into account. For example even though the location directly under the fluorescent light offers the highest energy potential, it is limited to 8.5 hours of light per day for 5 days per week, which is a total of 42.5 hours in a week. Outside these hours, no light is available for harvesting. With only 42.5 hours of light available for harvest per week, the average power generated at this location is 316µW. Table 2 shows the average power generated at all eight locations. The highest average power potential was found to be at the window location with 574µW, but this value is a best case scenario as the measurements were taken during the summer. This location will be significantly lower during winter and is highly dependent on outside conditions. The Desktop Light location showed very low average power as light is only available for 10 hours per week. During the winter the average energy levels available will be lower at all locations were natural light is harvested such as the window and bench locations.

TABLE 2 RESULTS FROM SURVEY OF DEPLOYMENT ENVIRONMENT

Location	**Light Level (Lux)**	**Light Hours (Per week)**	**Max Power (Watts)**	**Average Power (Watts)**
Bench	1100	112	88µW	58.6µW*
Fluorescent (facing up)	11000	42.5	1.25mW	316µW
Fluorescent (right angle)	2600	42.5	290µW	73.3µW
Desktop Light	3500	10	320µW	19µW
Corner 1	230	112	18µW	12µW*
Corner 2	150	112	30µW	20µW*
Window Location	5300	112	861µW	574µW
Ceiling (facing down)	250	112	46µW	33µW

** Best case scenario with 16 hours of natural light in summer*

D. Energy Storage

The previous section has provided an overview of the energy levels available within the office using the proposed harvester and highlighted the fact that energy needs to be stored for periods when no light is available for harvesting, such as at night.

As the energy harvester proposed in this paper incorporates a supercapacitor as the storage element, two sets of experiments were performed on real deployments: the first investigated the effect light density has on charge time at three locations (under a desktop light, under fluorescent light and in north facing window); the second investigated the capability of the supercapacitor to hold the energy over time by performing self-discharge tests on various sized supercapacitors. Two supercapacitors of 3F and 9F were selected for the tests to enable a fair comparison between size, capacity and cost.[8][9]

Figure 3 shows the charge profile of both the 3F and 9F supercapacitors using the proposed energy harvester at the three locations; as expected the smaller 3F charges quicker, as it does not have the ability to store as much energy as the larger 9F capacitor. The fastest charge times for both supercapacitors was shown to be at the location under fluorescent light, followed next by the window location. The desktop light location as expected showed the longest charge times. The maximum voltage charged on both the supercapacitors was 2.9V. The maximum voltage possible from the harvester is greater than 3.0 V at these locations, but due to internal losses within the supercapacitor this maximum voltage is never reached.

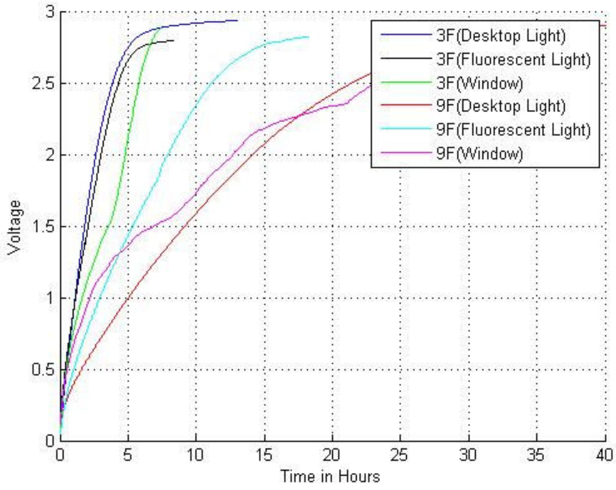

Figure 3 Charge Plots of 3F and 9F Capacitors at the three locations

Once the energy levels and charge times were identified, it was necessary to identify how much useable energy could be stored on the various sized supercapacitors. The first step was to find out how much energy could be stored on both the 3F and 9F supercapacitors when fully charged by the proposed light energy harvester.

Useable Energy Stored

The maximum voltage charge reached on both capacitors in the real deployment experiments was 2.9 V as shown in Figure 3. To calculate the energy stored on the supercapacitors, the following formula was used.

$$\text{Energy (Joules)} = 0.5*C*V^2$$

For the 3F supercapacitor the total energy stored was 12.6 joules

$$12.615 \text{ joules} = 0.5*3*(2.9^2)$$

While the 9F supercapacitor had a total of 37.8 joules stored

$$37.8 \text{ joules} = 0.5*9*(2.9^2)$$

It must be remembered that the wireless sensor [10] being powered has an operating range of between 1.8 V and 3.6 V, so the first 1.8 V is unusable energy. The first 1.8V of unusable energy stored on the supercapacitor is calculated for both the 3 and 9F supercapacitors as before and the result was 4.86 and 14.58 respectively. This unusable energy is then subtracted from the total energy, the result is 12.615 - 4.86 = 7.75 joules of useable energy on the 3F and 37.8 - 14.58 = 23.22 joules of useable energy on the 9F.

Once the energy values are known in joules, the next step is to convert them to a more useable unit of Ampere Hour (Ah).

$$\text{Ampere Hour (Ah)} = (\text{joules}/\text{voltage})/3600$$

The 7.75 joules of useable energy stored on the 3F is equivalent to 742µAh and for the 9F which has 23.26 joules, this is equivalent to 2.228mAh. With these ampere hour values it is possible to calculate the maximum lifetime of the wireless sensors during periods when no light energy is available for harvesting.

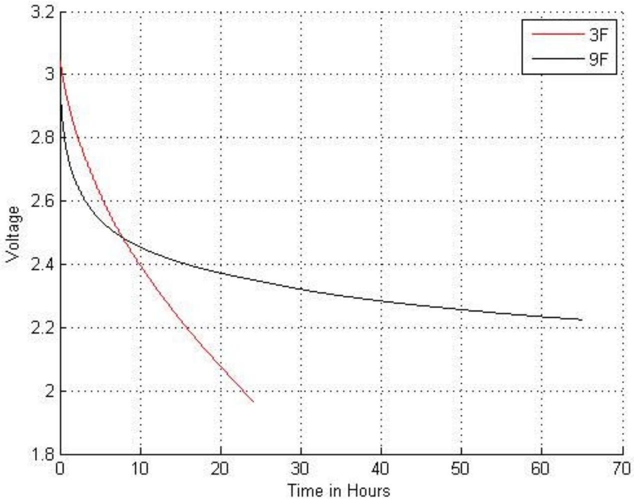

Figure 4 Self Discharge Plots of 3F and 9F Capacitors

The energy consumption of the wireless sensors is not the only factor which affects the lifetime of the device. One major disadvantage associated with supercapacitors which severely limits their ability to store energy for long periods of time is their self-discharge behavior. The self-discharge rate of both supercapacitors was measured by performing a simple voltage measurement once every minute using an Agilent 34411A Multimeter on the two fully charged supercapacitors. This multimeter was used as the input impedance is 10GΩ and has minimal effect on the measurements. The results of the experiment are shown in Figure 4 for both the 3F and 9F supercapacitors. As expected the 3F's voltage drops quicker than the 9F, with the voltage of the 3F dropping to 1.9 V after the first 24 hours compared to 2.5 V for the 9F supercapacitor. This self-discharge behaviour limits the lifetime of the wireless sensor even before any consideration of energy consumption.

E. Application Energy Usage

The final step before deploying the light energy powered wireless sensors is to evaluate the energy requirements. From this the designer can specify the supercapacitor to ensure that the WSN can continue to operate even during periods when no light is available such as at night, weekends and holidays.

Wireless sensors by their nature have very limited energy sources, so spend the majority of their time in low power sleep modes and only wake periodically to perform measurements and transmit the results to the basestation. The energy requirement of the wireless sensor node was evaluated for five different applications. The sleep times between measurements/transmissions for the five applications were 100 ms, 500 ms, 1 s, 10 s and 1 minute. The time needed to complete the measurements and transmit the results (18 Bytes) is 10ms at an average current consumption of 19mA. Table 3 shows the average power requirements of the wireless sensor for the five different applications tested.

Table 3 Power Requirements of Wireless Sensor

App	Active Time	Sleep Time	Avr Curr	Avr Pow
100ms	6sec	54sec	1.902mA	5.706mW
500ms	1.2sec	58.8sec	382.9µA	1.148mW
1 Second	0.60sec	59.4sec	192.97µA	578.91µW
10 Seconds	0.06sec	59.94sec	21.99µA	65.97µW
1 Minute	0.01sec	59.99sec	6.16µA	18.48µW

As expected the lowest application rate of 1 measurement/transmit per minute consumes the lowest amount of power at an average of 18.48µW and the highest application rate running at 100ms consumes the most power with an average consumption of 5.706mW. More importantly these results show that in reality the 100ms, 500ms and 1 second applications cannot be run on our proposed energy harvester powered wireless sensors as the power they require is greater than can be generated at any of the tested locations. For example the best deployment location was found to be directly under the fluorescent light and when the proposed harvester was tested at this location, the average power it could generate was found to be 316µW, which is less than the 578µW required by the 1 second application.

With the energy requirements of the wireless sensors acquired for the various applications, the final step is to calculate how long the wireless sensor can survive running these applications while being powered solely from the energy stored in the both the fully charged 3F and 9F supercapacitors. Depending on the deployment location, the light energy harvester powered wireless sensors will need to run on the energy stored in their supercapacitors during periods when no light is available for harvesting, such as at night and weekends.

Table 4 Calculated Expected Lifetime for Various Applications

App	3F Cap	9F Cap	Avr Curr	3F Life	9F Life
100ms	742µAhr	2.228mAhr	1.902mA	0.39 hrs	1.17hrs
500ms	742µAhr	2.228mAhr	382.9µA	1.94 hrs	5.82 hrs
1 Sec	742µAhr	2.228mAhr	192.9µA	3.85 hrs	11.5 hrs
10 Sec	742µAhr	2.228mAhr	21.99µA	33.7hrs	101 hrs
1 Min	742µAhr	2.228mAhr	6.16µA	120 hrs	360 hrs

The lifetime calculations in Table 4 show the expected lifetime of the different applications when being powered from either the 3F or 9F supercapacitors. From the previous section, it has been concluded that the proposed light energy harvester can meet the energy demands of both the 10 sec and 1 minute applications. From Table 4 it can be seen that if the energy harvester consists of a 3F supercapacitor, the maximum survival lifetime of the wireless sensor when no light is available for the 10 second and 1 minute applications is 33 and 101 hours respectively. However if the energy harvester consists of the 9F supercapacitor the survival time of the wireless sensor increases to 101 hours for the 10 second application and 360 hours for the 1 minute application. The 9F supercapacitor ensures that the 10 second application can remain running throughout the weekend and for this reason was used in the proposed energy harvester. These results all show the ideal maximum lifetime and do not take the effect of supercapacitor self discharge into account.

One possible method to extend the lifetime of the wireless sensor is to ensure that all energy stored on the supercapacitor is used. This can be achieved with the addition of a DC-DC Boost Converter, which regulates the output and ensures the wireless sensor continues to operation until all energy has been withdrawn from the supercapacitor (even energy from 0 - 1.8V). The disadvantage of this converter is that it puts an additional energy demand on the system. Initial experimental work carried out using a DC-DC convertor [11] found that the additional energy requirement of the DC-DC convertor outweighed the advantage of being able to extract all energy from the supercapacitor and in reality the lifetime of the wireless sensors was significantly reduced. For this reason the DC-DC convertor approach was not implemented in the proposed energy harvester.

Future work is planned to investigate using a range of the latest more efficient DC-DC convertors such as [12], to determine if it is possible to extend lifetime using this approach.

F. Full Node Discharge Test

The final set of experiments, are a repeat of the self-discharge tests in Figure 4 but now performed on the full wireless sensor running the 100ms, 500ms, 1 second and 10 second applications. The 1 minute application rate was not tested as the time needed to perform the experiments would have been very long. Figure 5 shows the discharge plots of the 9F supercapacitor when running the 100 ms, 500 ms, 1 s and 10 s applications. The results verify the findings of Table 4 and as expected show that the lifetime of the wireless node reduces as duty cycle increases. These results also validate that the light energy harvester deployed directly under the fluorescent light using a 9F supercapacitor and running the 10 s application can survive 100 hours without light.

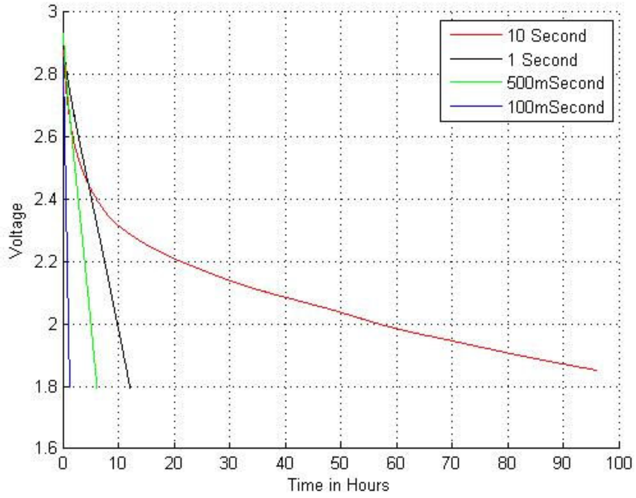

Figure 5 Voltage Discharge of 9F Capacitor with Wireless Sensor

G. *Deployment Test*

The previous sections of the paper have shown that using the proposed simple light energy harvester deployed within a typical office environment, it is possible to harvest enough energy to power typical wireless sensors and ensure that they can continue to operate during nights and over weekends, when no light energy is available for harvest. The final step was to validate the findings and verify the long-term capability of the system by deploying two wireless sensors powered by the proposed light energy harvester. These wireless sensors were deployed directly under the fluorescent light and in the window location, as they showed the highest energy potential. Figure 6 shows the proposed light energy harvester powering the wireless sensor.

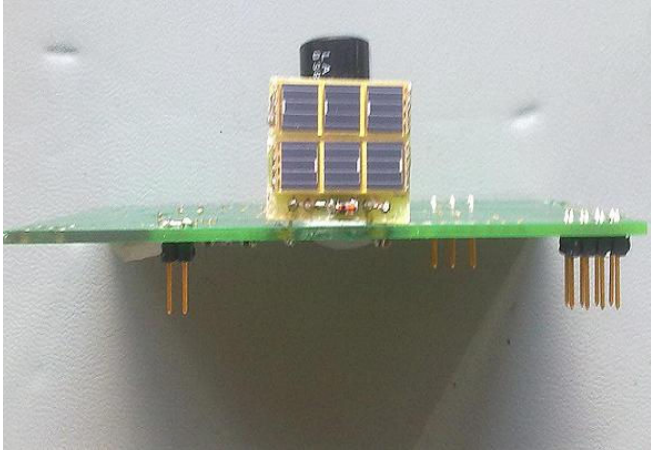

Figure 6 Proposed Light Energy Harvester powering wireless sensor

Figure 7 shows the voltage plot of the light energy harvester powered wireless sensor deployed directly under the fluorescent light while running a 10 second application for a full week, starting 12.00AM Monday morning. The voltage is shown to drop significantly at night and over the weekend when the lights are turned off. At 9.00AM on Monday morning following the weekend when no light was available for harvest, the voltage has dropped to 2.15V which is still well above the 1.8V shut down threshold of the device. From 9.00AM Monday morning, once the lights are turned on, the harvester quickly charges up to 2.8V (full charge) within 7 hours.

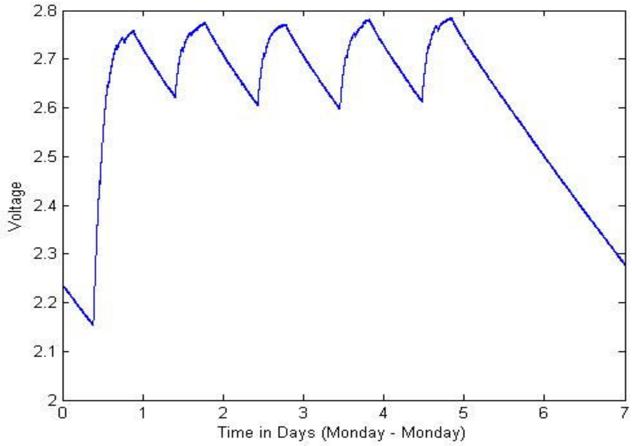

Figure 7 Voltage Plot of the light energy powered wireless sensor deployed under the fluorescent light

The five working days (Monday – Friday) can clearly be seen, as the voltage drops down to approximately 2.6V each night and then rises back to full voltage during the day. After the fifth day (Friday), the voltage drops off during the night and continues to fall during the weekend when no light is available. A 100 day deployment of the harvester at this location validated the long term suitability of the harvester, as over 860,000 measurements and transmissions were successfully performed. At no stage during the 100 day test did the wireless sensor brown-out or reset as the voltage never dropped below 1.9V.

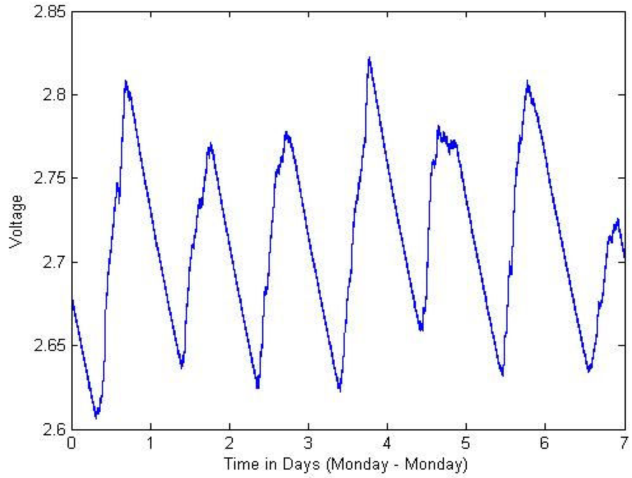

Figure 8 Voltage Plot of the light energy powered wireless sensor deployed in window location

Figure 8 shows the voltage plot of the light energy harvester powered wireless sensor running the 10 second application but this time deployed in the window location. This voltage plot was taken over the same seven day period as in Figure 7. As with the previous plot, it can be seen that the voltage drops at night when there is no light to harvest and rises during the day. When the energy harvester was deployed directly under fluorescent light, the voltage dropped to 2.15V during the weekend. Figure 8 shows that the minimum voltage measured at the window location during the same period was 2.61V, as this location has the advantage of available light even at the weekends. Figure 8 also highlighted how the maximum voltage of the energy harvester at this location varied from day to day. The maximum voltage reached by the harvester was 2.82V on day 4 (Thursday), while on day 7 (Sunday), the charge voltage only reached 2.72V. This variation in voltage is due to the varying light conditions outside. A long term 100 day deployment was also performed at this location and again over 860,000 measurements and transmissions were performed successfully. As with the previous long term deployment, at no stage during the 100 day test did the wireless sensor brown-out or reset. At this location the minimum voltage measured on the energy harvester during the 100 days was 2.58V, as at this location light is available at the weekends. The long term deployment tests of the harvester validated that it is possible to source enough energy from indoor light sources to not only power a typical wireless sensor application, but also guarantee continued operation for over 100 hours in the event that no light energy is available for harvesting.

III. CONCLUSIONS

Following a review of light energy harvesting approaches and components, a simple low cost, low component count light energy harvester has been proposed, consisting of just two small photovoltaic cells, a diode and supercapacitor. The proposed circuit weighs just 7 grams and measures 25 x 22 x 20mm, with the result being that it can easily be incorporated into existing WSNs. An initial survey method of the deployment environment was presented with the aim of providing the designer with a better understanding of the typical energy levels available from the proposed harvester at various locations within an indoor office environment.

The performance of the light energy harvester has been verified, by successfully deploying a WSN powered by harvesters in a typical office environment; with light only available for 40 of the 168 hours per week. This test confirmed that the supercapacitor based harvester meets the energy requirements of a low power wireless sensor network and is capable of powering the network over weekends and during holiday periods when no light is available.

To further verify the long term suitability of the harvester a 100 day deployment was performed with two wireless sensors powered by the proposed harvester. These wireless sensors were located directly under a fluorescent light and close to a north facing window, during this deployment over 860,000 packets were successfully transmitted by each wireless sensor. The minimum voltage experienced during the 100 day deployment for wireless sensors at the locations under the fluorescent light and in the window were 1.91V and 2.58V respectively.

This work validates that by using the proposed simple harvester it is possible to harvest enough energy from indoor light sources to power a wireless sensor network for low power applications, even in locations where light is often unavailable for long periods of time.

IV. REFERENCES

[1] J. M.Gilbert and F Balouchi "Comparsion of energy harvesting systems for wireless sensor networks," *Int.J.Autom.Comput.,* vol.5, pp.334-347, 2008.

[2] D Brunelli, C.Moser, L.Thiele and L.Benini "Design of a solar-harvesting circuit for batteryless embedded systems," Circuits and Systems I: Regular Papers, *IEEE Transactions on,* 56(11):2519-2528,November 2009.

[3] S. Bader and B. Oelmann, "Enabling battery-less wireless sensor operation using solar energy harvesting at locations with limited solar radiation," in *Proc. Fourth Int Sensor Technologies and Applications (SENSORCOMM) Conf*, 2010, pp. 602–608.

[4] W. S. Wang, T. O'Donnell, L. Ribetto, B. O'Flynn, M. Hayes, and C. O'Mathuna, "Energy harvesting embedded wireless sensor system for building environment applications," in *Proc. 1st Int. Conf. Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology Wireless VITAE 2009*, 2009, pp. 36–41.

[5] IXYS Solar "EVIX-CX3AA Application Note", [Online] http://www.ixys.com/pdf/EVIX-CX3AA_app_note.pdf

[6] IXYS Solar "XOB17 SolarBit Datasheet", 2009. [Online]:http://www.ixyscolorado.com/pdf/XOB17_Solar_Bit_Datasheet_Jun%202009_color.pdf

[7] Vishay Semiconductors "BAS281, BAS282, BAS283 Small Signal Schottky Diodes Datasheet", 2010 [Online] http://www.vishay.com/docs/85500/bas281.pdf

[8] Taiyo Yuden "9F SuperCapacitor Datasheet", 2011 [Online]:http://www.yuden.co.jp/ut/product/pdf/capacitor02_e.pdf

[9] Cooper Bussman PowerStor "3F SuperCapacitor Datasheet" [Online] http://www.cooperindustries.com/content/dam/public/bussmann/Electronics/Resources/Data%20Sheets/Bus_Elx_DS_4308_PM_Series.pdf

[10] WiSAR Lab "WiSAR Lab Development Mote" [Online] http://www.wisar.org/

[11] Texas Instruments "TPS61200 Datasheet", 2008. [Online] http://focus.ti.com/lit/ds/symlink/tps61200.pdf

[12] Texas Instruments "TPS61097-33 Datasheet", 2009. [Online] http://focus.ti.com/lit/ds/symlink/tps61097-33.pdf